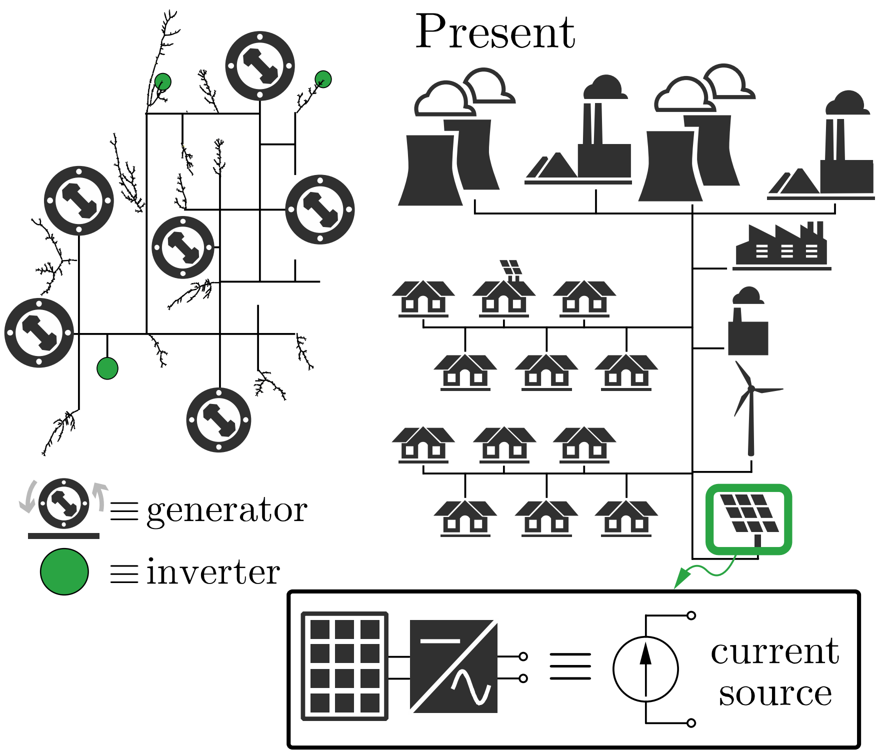
Grid-Forming Inverters – Enabling the Next Generation Grid

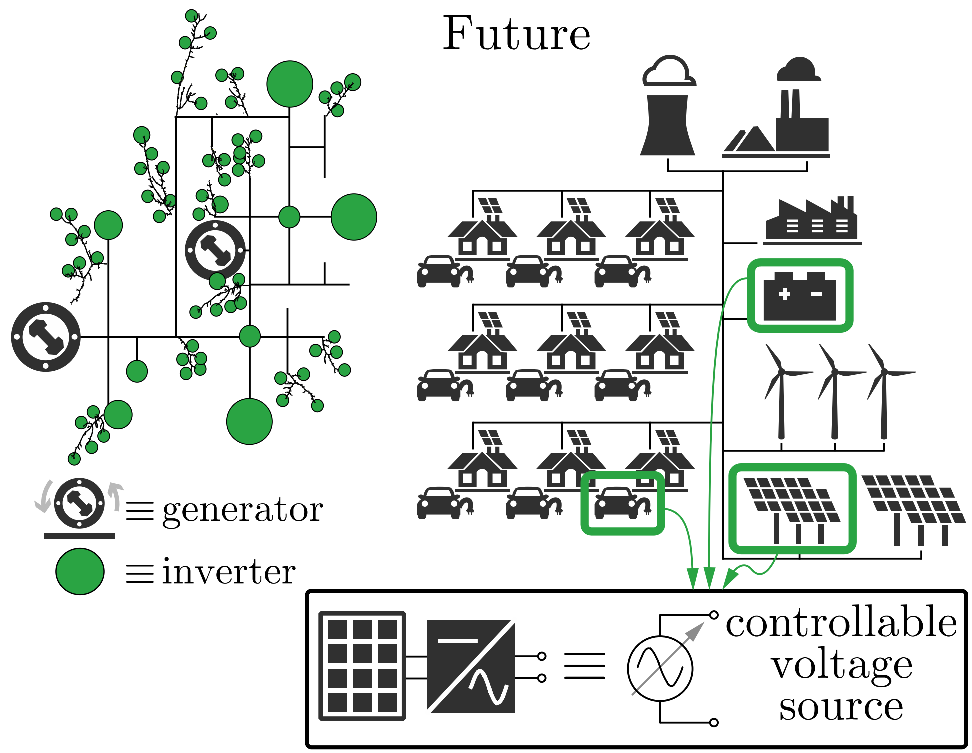
Yashen Lin

PEGI workshop

10/13/2020

Next Generation Grid



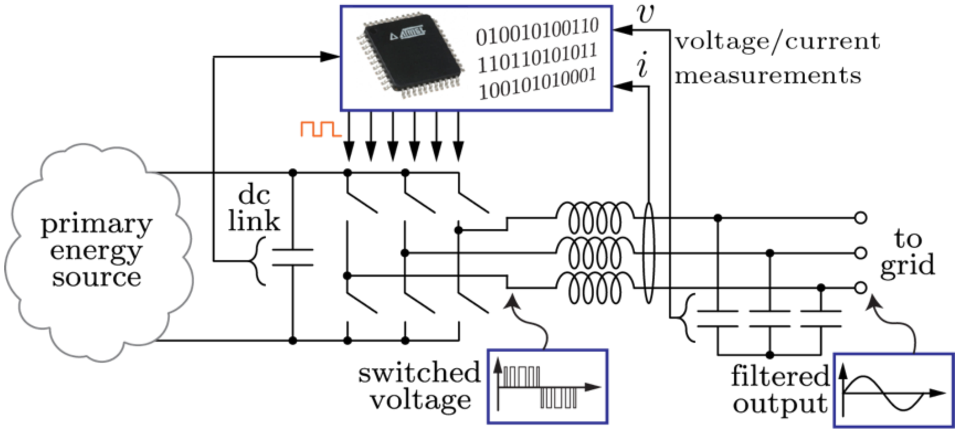


Grid-following controls → To next-generation grid-forming controls

Grid-Forming Inverters

Grid-Forming Inverters

- **Inverter-base resources**

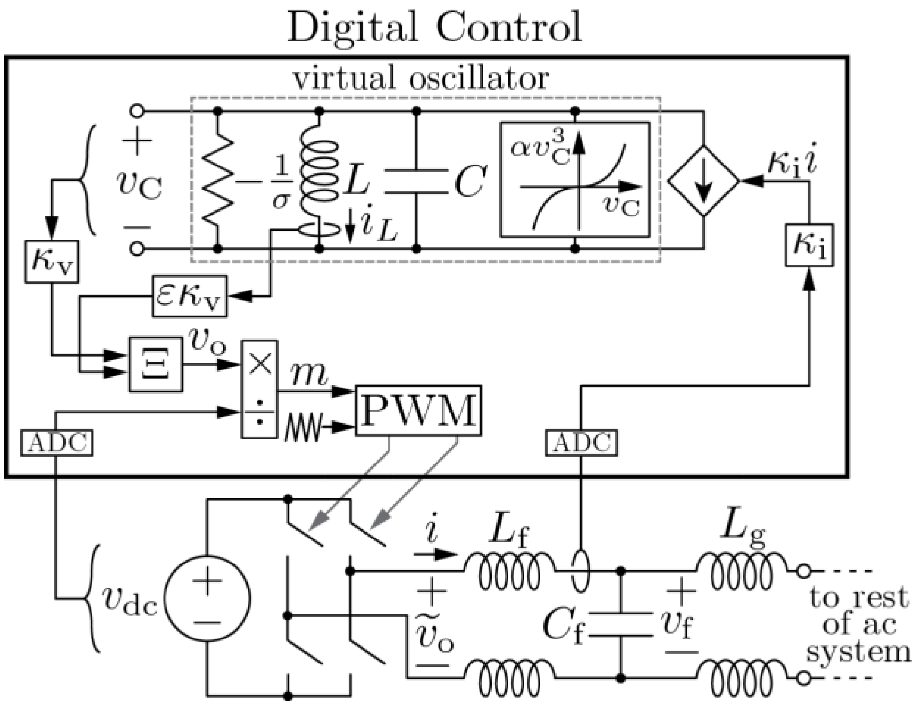


- **Grid-forming inverter control**
  - Regulate terminal voltage
  - Islanded operation, maintain grid stability, black start, etc.
  - Types of grid-forming inverter control: droop [1], virtual synchronous machine [2], virtual oscillator controllers (VOC) [3]

[1] Chandorkar, M.C., et.al. 1993. "Control of Parallel Connected Inverters in Standalone ac Supply Systems." IEEE Transactions on Industrial Applications.
[2] Beck, H.-P., and R. Hesse. 2007. "Virtual Synchronous Machine." Proceedings of the Electrical Power Quality and Utilisation (EPQU 2007).
[3] Johnson, B.B., et al. 2016. "Synthesizing Virtual Oscillators to Control Islanded Inverters." IEEE Transactions on Power Electronics.

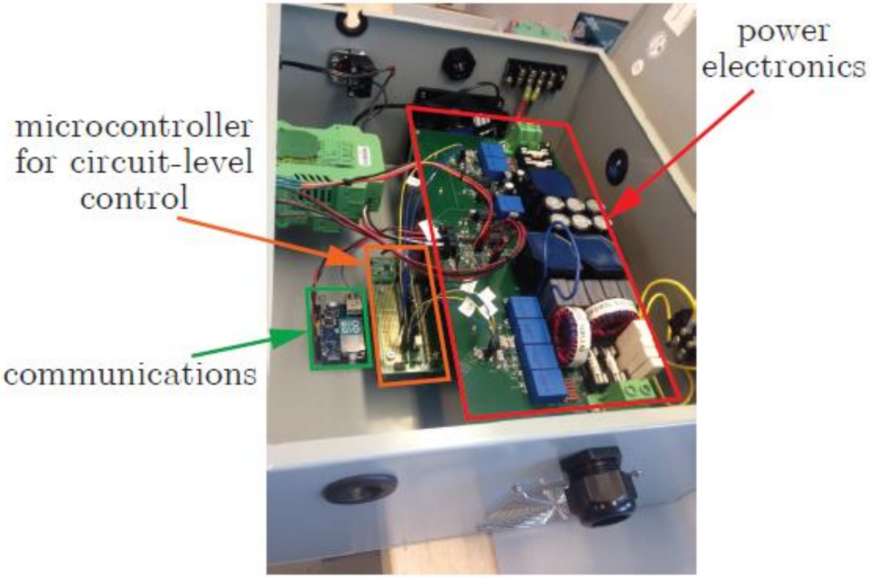
Virtual Oscillator Controller (VOC)

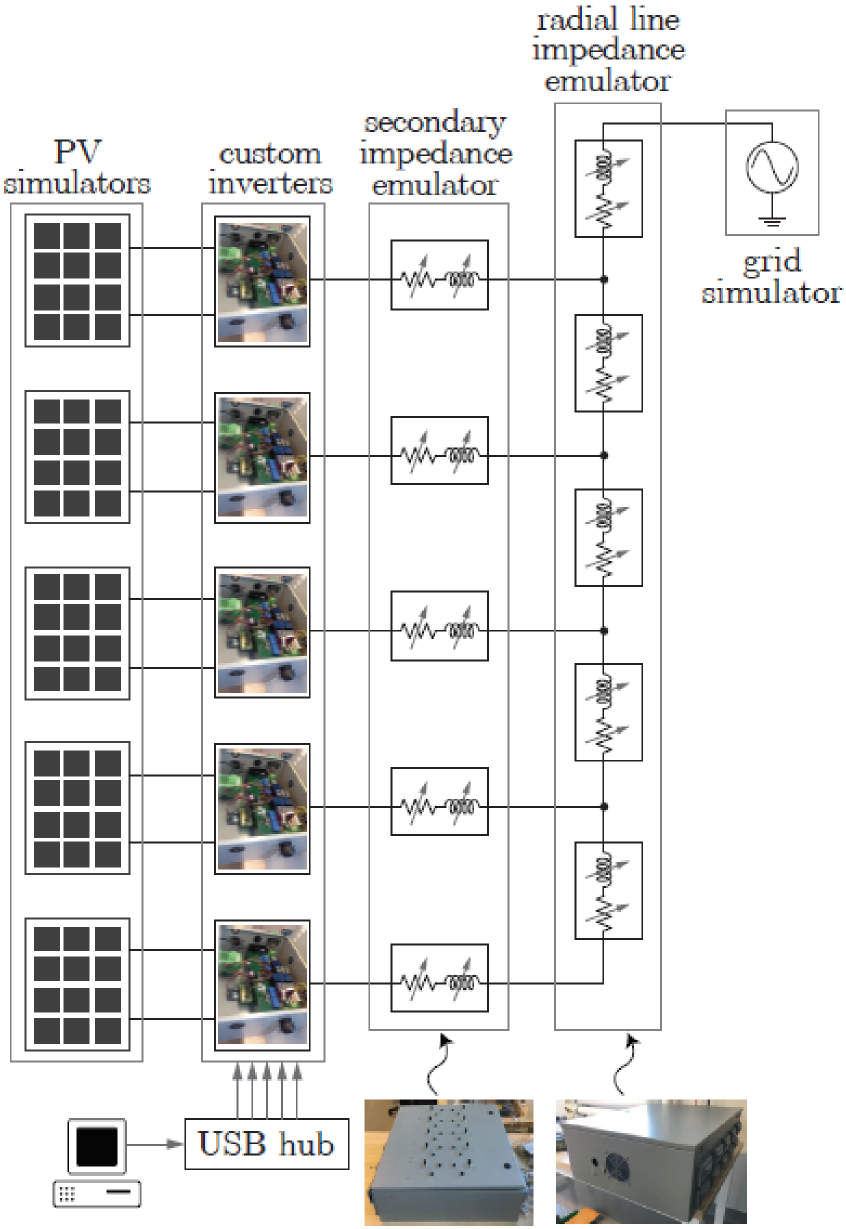
- VOC is a time-domain control approach in which the inverter is programmed (through its digital controller) to emulate the dynamics of a non-linear electrical oscillator.
    - Synchronize among multiple units; droop-like behavior
    - Does not require power filters



Hardware testing

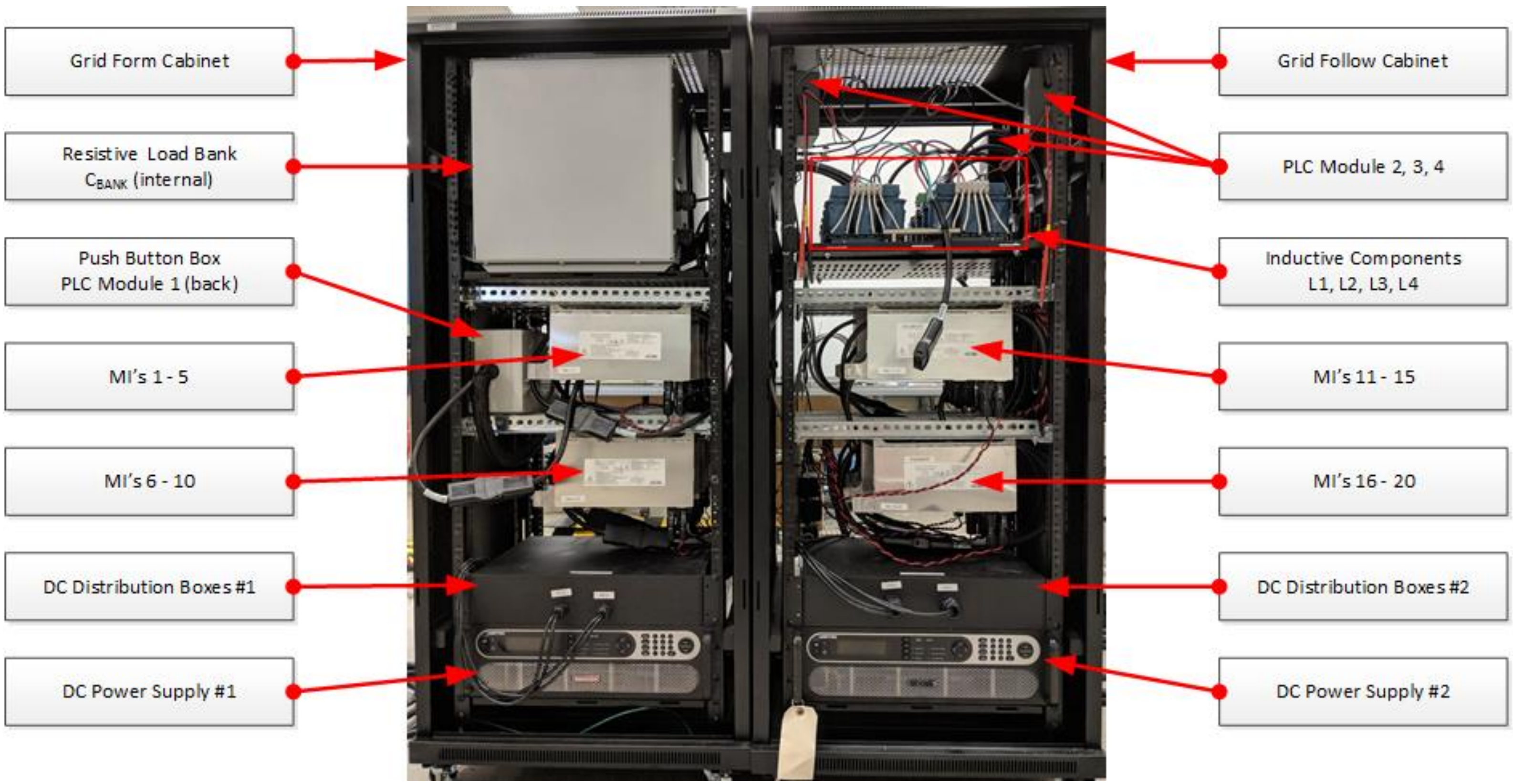
- **Customized test bed**



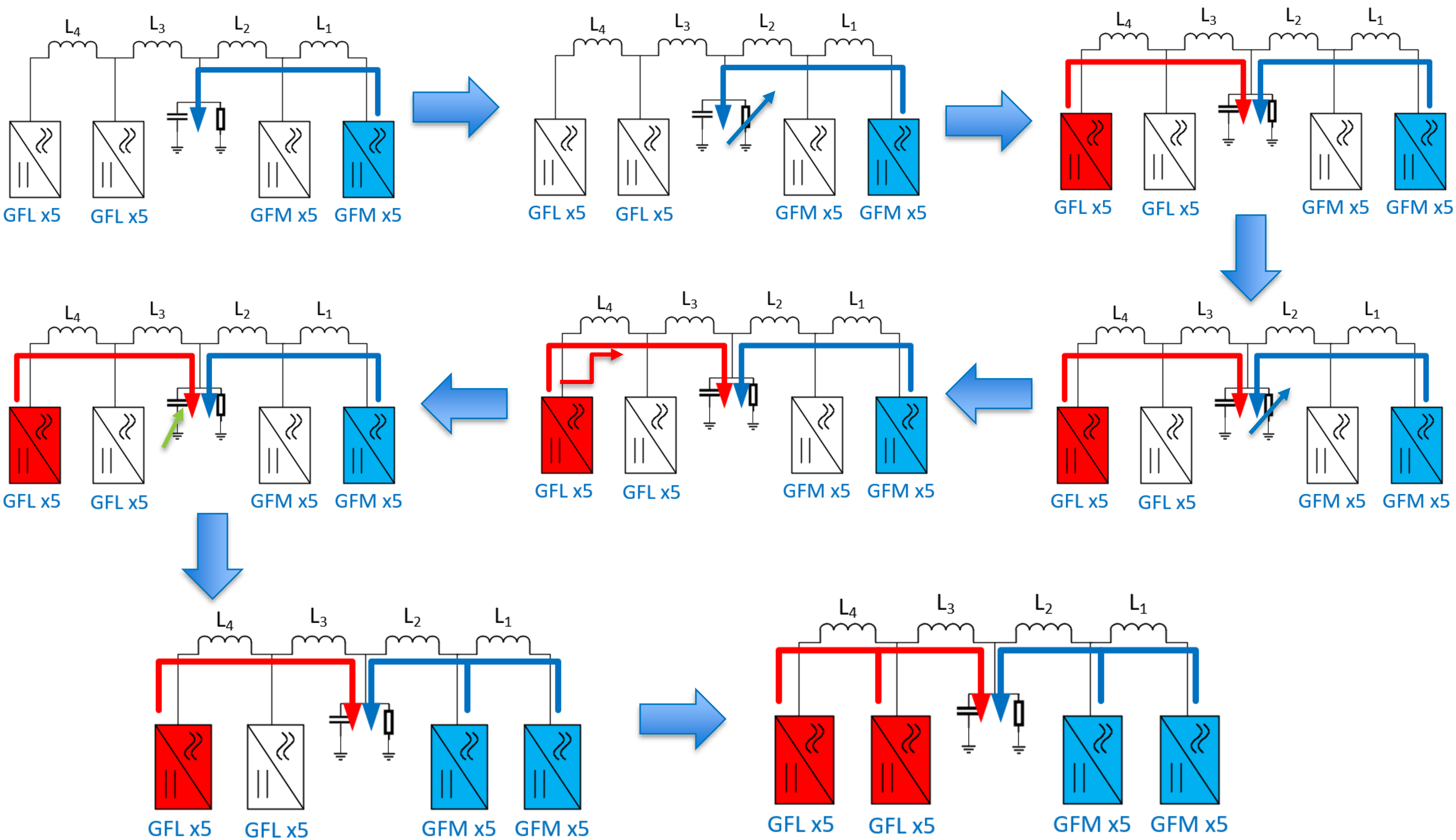


Hardware testing

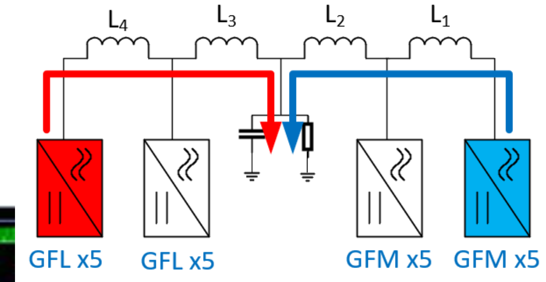
- **Commercial micro-inverter test bed**
  - 20 SunPower micro-inverters

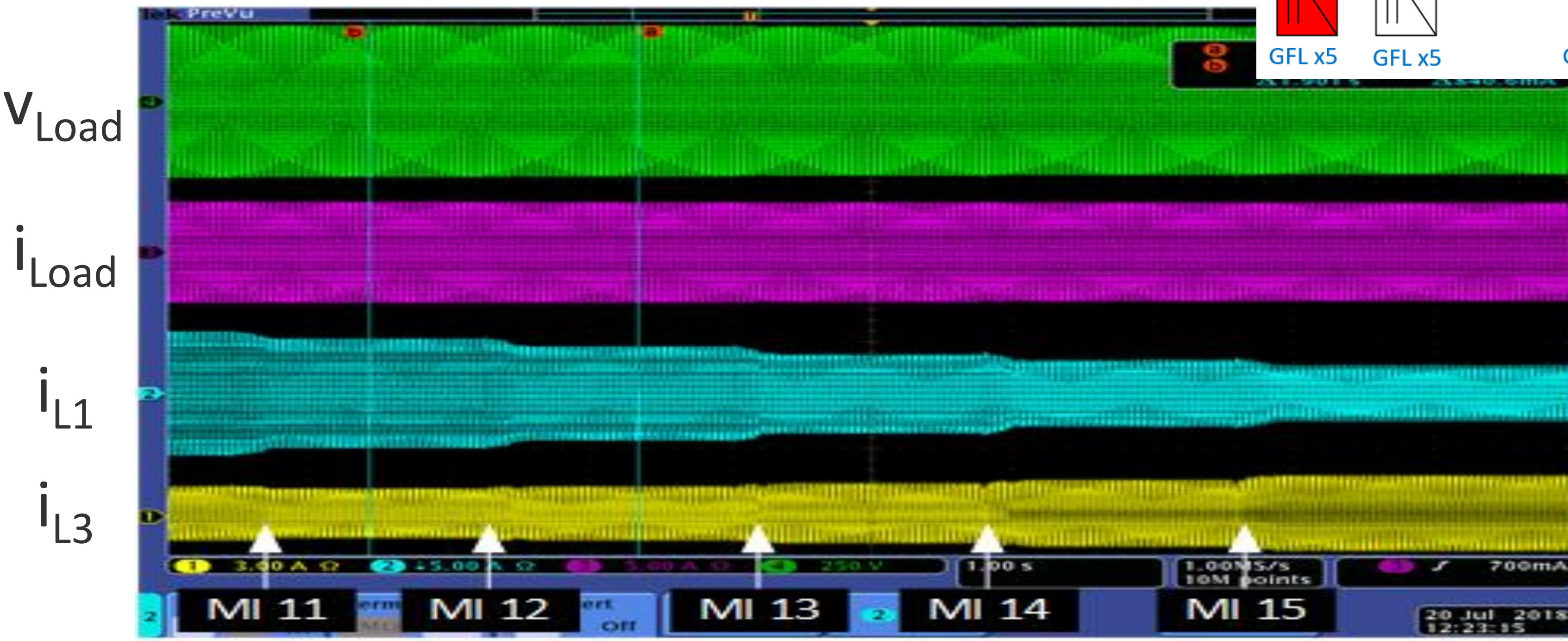


Hardware testing



Hardware testing

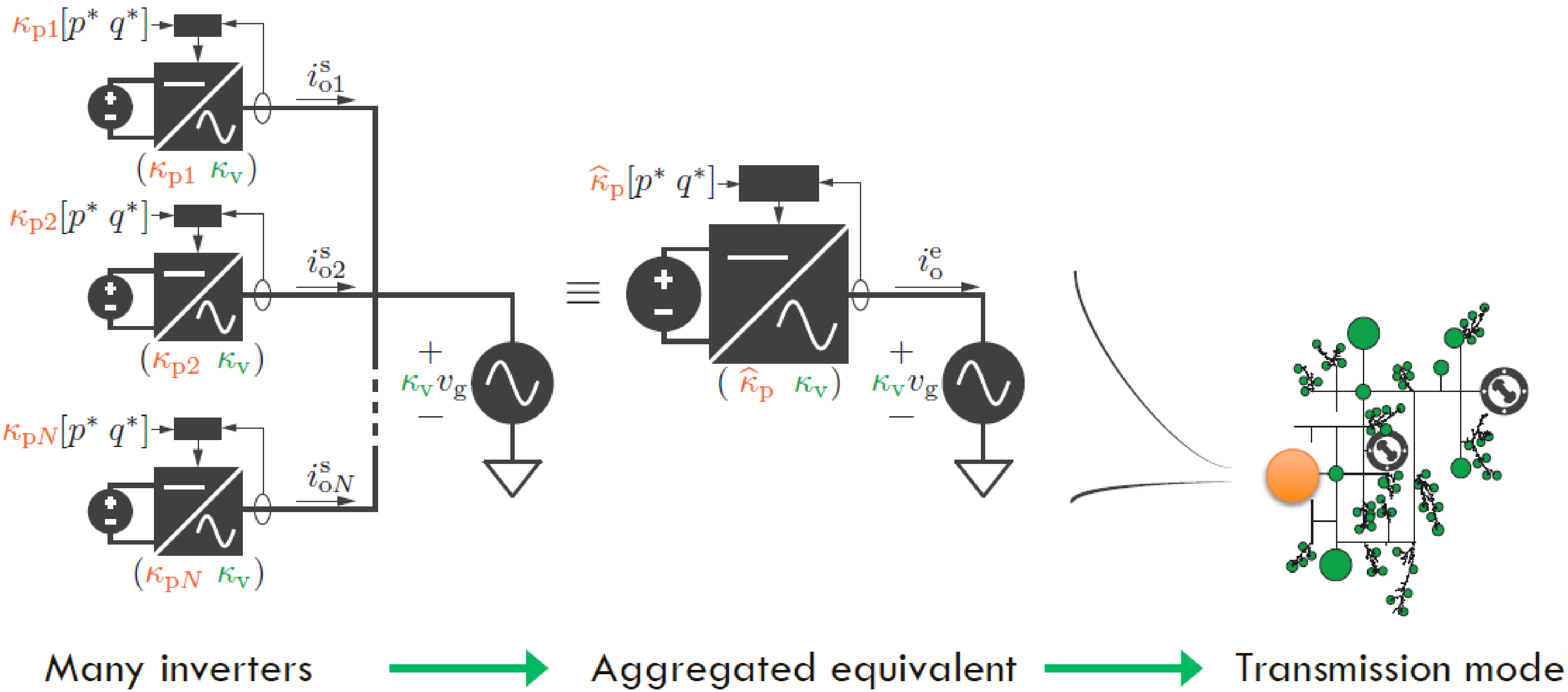




- VOC inverters are able to regulate the output voltage.
- VOC inverters are able to black start the system.
- Multiple VOC inverters can dynamically share loads.
- VOC inverters work well when connected with grid-following inverters.

Inverter Aggregation

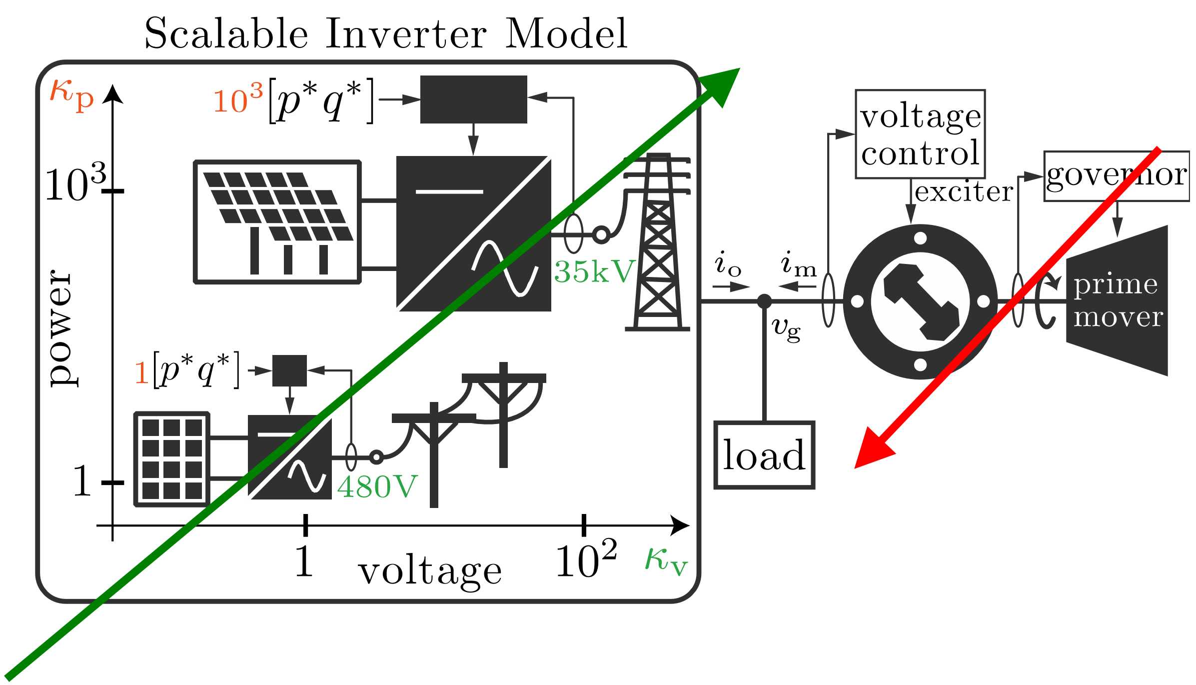
- **How to represent a large number of inverters?**
  - Scaling law to determine the aggregated model parameters



[1] Purba, V., et.al. 2018. “Reduced-Order Aggregate Model for Parallel-Connected Single-Phase Inverters.” IEEE Transactions on Energy Conversion.
[2] Khan, M.M.S., et.al. 2018. “A Reduced-Order Aggregated Model for Parallel Inverter Systems with Virtual Oscillator Control.” Proceedings of the 2018 IEEE 19th Workshop on Control and Modeling for Power Electronics (COMPEL).

Stability Analysis

- **Stability analysis: What happens as the ratio of inverter/machine ratings increases?**
  - A simple illustrative example system:
  - Adjust the ratings of the inverter and machine to represent different inverter penetration level.



[1] Lin, Y., et. al. 2017. "Stability Assessment of a System Comprising a Single Machine and Inverter with Scalable Ratings." 2017 North American Power Symposium (NAPS).

Stability Analysis

- Examined single-machine single-inverter system, and multi-unit systems (20 MI system, IEEE 39-bus system).

- Summary of results:
  - Coupled inverter-machine system may become small-signal unstable when we increase the inverter penetration level.
  - The “tipping point” where the system becomes unstable depends on system parameters.
  - Grid-forming inverter can potentially improve the stability of the system.

Dispatchable-VOC

- dVOC allows users to specify power setpoints for each inverter.
- If no setpoints are given, dVOC subsumes VOC control and inherits all its favorable dynamical properties.
- dVOC is asymptotically stable in 100% inverter system.
- Validated in NREL hardware test bed.

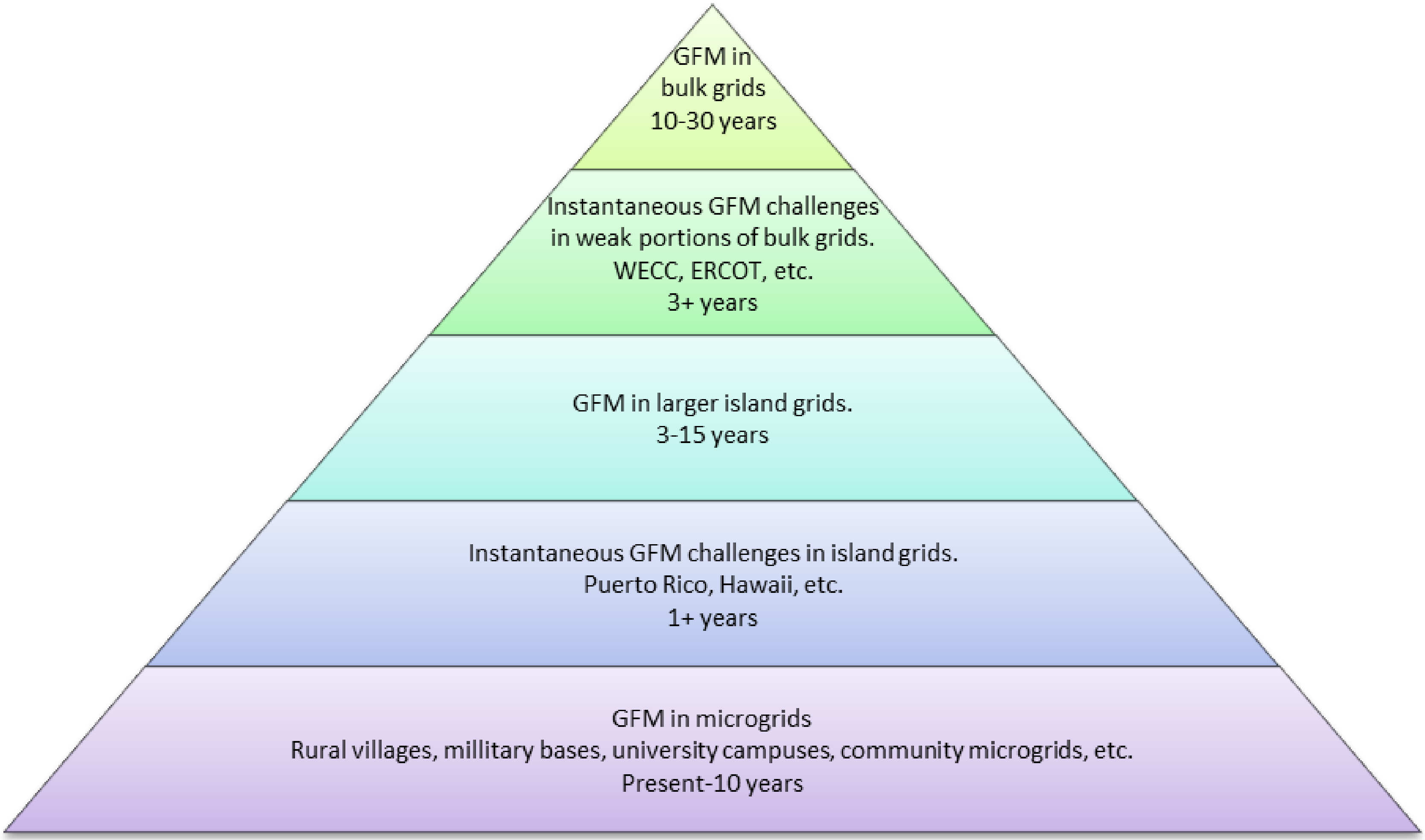
[1] Seo, G., et al. "Dispatchable virtual oscillator control for decentralized inverter-dominated power systems: Analysis and experiments." 2019 IEEE Applied Power Electronics Conference and Exposition (APEC).

Research Roadmap on Grid-Forming Inverters

Research Roadmap

- **Team collaboration**
  - NREL, SNL, LBNL, Univ of Washington, Univ of Wisconsin, DOE SETO
- **Feedback from experts with diverse background**
  - Grid-forming inverters for low-inertia power system workshop
- **To be published**

Research Roadmap



Research Roadmap

- **Near-term research priorities:**
  - The review of regulatory and technical standards.
  - The development of advanced modeling techniques.

- **State-of-the-Art Inverter Controls and Open Research Directions:**
  - Frequency Control
  - Voltage Control
  - System Protection
  - Fault Ride-Through and Power System Recovery
  - Modeling and Simulation Approaches

Frequency Control

- **Classic frequency control:**
  - Hierarchical: primary, secondary, tertiary

- **Open research questions:**
  - What are the issues related to GFM inverters providing for loss of inertia?
  - What signals, if any, must be communicated between distribution-level inverters and system operators?
  - Can heterogeneous systems containing GFL inverters, GFM inverters, and machines operate together to guarantee frequency regulation and stability?
  - What shares of rotating generators and GFL and GFM inverters can guarantee power system stability?
  - How important is frequency regulation in a system dominated by power electronics?

Voltage Control

- **Classic voltage control:**
  - Generally, reactive power control

- **Open research questions:**
  - How do thousands of GFM and GFL inverters at medium voltages and lower affect system voltage stability and control?
  - How should VAR flow be controlled—at each inverter, at locally aggregated inverters, or through a coupled communication networks?
  - What are the interactions between machine excitation systems and inverters with either GFM or GFL controls? Can inverter and machine-side controls be tuned to eliminate such interactions?

System Protection

- GFL inverters can negatively affect protection system, GFM maybe able to alleviate the issue, but very few study on actual effects of GFM on protection.

- **Open research questions:**
  - Short-circuit response of GFMs including the effect of control schemes?
  - The ability of GFMs to produce zero- and negative-sequence fault current under unbalanced fault events?
  - GFM dynamic response and its effect on Out-of-Step protection Tripping (OST) and Power Swing Blocking (PSB) protection at the transmission level?
  - Analytical and simulation models for GFM under fault scenarios?
  - Anti-islanding with GFM?

Fault Ride-Through and System Recovery

- Capability to remain connect to the grid through abnormal transients; prevent system level cascading events.
- No trip zone determined by simulations of the current system.

- **Open research questions:**
  - Will modern FRT grid codes apply to power systems with high penetrations of inverter-based generation with GFM controls?
  - How does the FRT codes need to evolve?
  - What voltage regulation capability will inverters with GFM controls need to provide to recover grid voltages after faults?
  - How to control GFM to remain in the no trip zone? What tools are needed for this analysis?
  - How should FRT codes be coordinated with the operation of protective relays?

Modeling and Simulation

- Positive sequence model and simulation tools based on the assumption that frequency remains close to nominal during fault.
- Fast dynamics from inverters may render this assumption invalid.
- EMT simulation captures more dynamics but high computational burden.

- **Open research questions:**
  - What is the appropriate inverter-based generations model for existing positive-sequence simulation tools?
  - What modeling fidelity of the transmission system and inverter-based generation is necessary/appropriate for a comprehensive study on electric grids undertaking large transients?

Acknowledgement

- **Sponsor**

SOLAR ENERGY TECHNOLOGIES OFFICE
U.S. Department Of Energy

- **Collaborators**
  - NREL: Gab-Su Seo, Hugo Villegas Pico, Marcello Colombino
  - Univ of Washington: Brian Johnson
  - Univ of California Santa Barbara: Francesco Bullo
  - Univ of Minnesota: Sairaj Dhople
  - SunPower: Patrick Chapman
  - LNL: Joseph Eto
  - SNL: Abraham Ellis, Jack Flicker, Brian Pierre
  - Univ of Wisconsin: Robert Lasseter

Thank you!

Yashen.Lin@nrel.gov

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This work was authored by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Funding provided by U.S. Department of Energy Office of Energy Efficiency and Renewable Energy Solar Energy Technologies. The views expressed in the article do not necessarily represent the views of the DOE or the U.S. Government. The U.S. Government retains and the publisher, by accepting the article for publication, acknowledges that the U.S. Government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this work, or allow others to do so, for U.S. Government purposes.

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